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ACOUSTIC PROPERTIES OF SEDIMENTS AT WEAPONS TEST RANGES OF THE NAVAL UNDERSEA WARFARE ENGINEERING STATION, KEYPORT, WASHINGTON

by

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Prepared for:
Research and Engineering Department
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Estimates are made of sound absorption and sound speed characteristics of sediments at the Dabob Bay and Keyport Shallow Water ranges operated by the Naval Undersea Warfare Engineering Station using empirical models developed by Hamilton and mean grain size and porosity data measured in samples collected by the authors. Data reported by earlier investigators permit estimates to be made also for sediments at the Nanoose and Jervis Inlet ranges. The purpose is to provide information which can be used in the design and evaluation of acoustic imaging devices which may be able to ease the problems

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of locating and recovery of torpedoes which became buried in the sediments. Field and laboratory procedures are described. Also reported are the results of measured sound speeds in a number of the gravity core samples. The most common surficial sediment is a soft, saturated silty-clay mud. For such sediments the sound absorption coefficient, α in dB per meter should be given approximately by α = 0.1 F where F is the sound frequency in kHz. It is concluded that sound absorption in these sediments, although not small, should not preclude the short range use of an acoustic imaging system operating at moderate frequencies. The possibility and the consequences of the existence of gassy sediments is discussed.

ABSTRACT

Estimates are made of sound absorption and sound speed characteristics of sediments at the Dabob Bay and Keyport Shallow Water ranges operated by the Naval Undersea Warfare Engineering Station using empirical models developed by Hamilton and mean grain size and porosity data measured in samples collected by the authors. Data reported by earlier investigators permit estimates to be made also for sediments at the Nanoose and Jervis Inlet ranges. The purpose is to provide information which can be used in the design and evaluation of acoustic imaging devices which may be able to ease the problems of locating and recovery of torpedoes which became buried in the sediments. Field and laboratory procedures are described. Also reported are the results of measured sound speeds in a number of the gravity core samples. The most common surficial sediment is a soft, saturated silty-clay mud. For such sediments the sound absorption coefficient α in dB per meter should be give approximately by $\alpha = 0.1\ F$ where F is the sound frequency in kHz. It is concluded that sound absorption in these sediments, although not small, should not preclude the short range use of an acoustic imaging system operating at moderate frequencies. The possibility and the consequences of the existence of gassy sediments is discussed.

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1. Introduction

The Naval Undersea Warfare Engineering Station (NUWES) and the Naval Postgraduate School (NPS) are jointly investigating the efficacy of acoustic imaging for the timely location of embedded torpedoes. Negatively buoyant torpedoes at end-of-run have penetrated the Dabob Bay and Nanoose range mudlines and become buried many feet below the surface.

Depending on torpedo trajectories following shutdown the unit can either enter the mud at a high pitch angle and bury nearly vertically to the tail or deeper, or enter at a low pitch angle and travel a significant distance before coming to rest in a nearly horizontal position some 5 to 10 feet below the mudline. Ideally, the acoustic imaging system should be useful both for locating the torpedo and for indicating the torpedo attitude and depth in the sediment or mud.

The acoustic imaging work is directed first at measuring and estimating various acoustic properties of sediments in Dabob Bay, Nanoose (Strait of Georgia), Keyport Shallow Water Range (SWR) and contiguous areas to the SWR, in order to determine sound absorption and reflection characteristics and, particularly, any similarities which may exist in these properties. After this the next steps will entail:

a. Selection of a convenient shallow water test site in which to bury an object which may simulate a torpedo shape;

b. Measurements of bottom reflectivity and reverberation at the test site; and

c. The initial test and evaluation of a prototype imaging system using a test buried torpedo.

The detection range and the resolution for any acoustic imaging system is a complicated function of frequency of the sound waves used. The resulting system represents a compromise between several factors,

among which are:

a. The dependence of sound absorption on frequency. In most fluids and solids this usually increases with a frequency increase.

b. The sound frequency dependence of interfering effects such as ambient noise, scattering from inhomogeneities in the medium and reflections from the target itself.

c. The effect of the size of the acoustic system and the acoustic wavelength on bearing and spatial resolution. Usually this resolution will increase with an increase of frequency for a system of fixed dimensions.

The prototype acoustic-imaging equipment design will be based partially on attenuation-determining parameters such as the range of sediment grain size, porosity, and sound speed characteristics. This report documents and discusses the above sediment characteristics for cores obtained at the locations listed in Tables 1 and 2 and shown in Figures 1, 2 and 3 . The short cores recovered at locations 6 and 15 in roughly 200 feet of water in Dabob Bay were obtained to determine foundation design constraints for a potential underwater structure.

Abstracts from data reports of other groups[1,2] on samples collected in earlier studies are included in this report. These data provide a basis for estimating acoustic properties of sediments on and near the ranges at Nanoose and Jervis Inlet.

II. Sediment Sample Collection and Storage

The facilities and crews of the boats IX 308 and NS-11 provided support for the collection of samples. We gratefully acknowledge the assistance of the crewmen who so skillfully operated the winches, cranes, and the boats during these operations.

For sample-taking in Dabob Bay from the IX 308, a gravity corer and a Shipek grab sampler were used. The gravity corer, only, was used in the Keyport area collections from the NS-11.

The two-inch gravity corer was released by a trip mechanism some 10 to 16 feet above the bottom and propelled into the sediment by a 200-pound weight stand. Various core barrel lengths, from 3 feet to 12 feet, were used at different times. The maximum length of sediment in the plastic core liner was about four feet, even though the corer penetrated, at times, to depths of 12 feet in the sediment.

The free-fall height (distance between bottom of gravity corer and water sediment interface) set into the trip line was about 15 feet for the Dabob Bay collections and about 10 feet for the operations from the NS-11 near Keyport. The reduced free-fall height was necessitated by lift height limitations of the smaller crane aboard the NS-11.

It was not feasible to carry the sediment sound speed measuring apparatus aboard the range craft, so the cores were stored by stacking them (in their liners) in garbage cans for later laboratory measurements. The cans were filled with water to reduce dehydration of the cores during a six-day storage period. The storage area used was the unheated rear entrance bay of Building 717 at Bangor. Ambient temperatures in this space were 6° to 10° C most of the time.

III. Sediment Sound Speed Measurements

A. Methodology

Values of sound speed in the sediments were determined in the laboratory using the Model USI 101 Sediment Velocimeter, built by Underwater Systems, Inc. This instrument provides means for measuring the time delay between the generation of an acoustic pulse at one transducer and its arrival at a second transducer. The acoustic path between them is a core liner filled with either sediment or "standardizing" fresh water. By noting the difference in time delays for the sediment-filled core liner and for a water-filled core liner of the same nominal dimensions (internal diameter and liner wall thickness), the sediment sound speed, C_w, can be calculated from the known sound speed in water, C_w, using

$$C_s = \frac{C_w}{1 - \frac{t\,C_w}{d}}$$

where d is the inside diameter of the core liner and $t = t_w - t_s$, where t_w and t_s are the measured time delays for the pulse for the water and sediment, respectively.

The acoustic pulse is "shock excited" in the transducer by a sharp voltage spike. The dominant frequency is about 450 kHz. Time delays were measured to the peak of the first arrival as displayed on the delayed sweep of a cathode ray oscilloscope.

Sound speed in the water was calculated using the empirical model given by Medwin[3]. This formula is

$$c = 1449.2 + 4.6\,T - 0.055\,T^2 + 0.00029\,T^3 + (1.34 - 0.010\,T)(S - 35) + 0.016\,Z$$

where c = sound speed in meters per second

T = temperature, degrees Celsius

S = salinity in parts per thousand

Z = depth in meters

Although this model is not as accurate as that of Del Grosso (V.A. Grosso, "New Equation for the Speed of Sound in Natural Waters (with comparisons to other equations", J. Acoust. Soc. Am. 56, 1084-1091 (1974) the maximum error is not more than about 0.5 meter/second which is well within experimental uncertainties for the sediment sound speed measurement reported here. This formula was also used to correct measured speeds in the samples to the temperature of 10°C.

B. Accuracy

The precision with which the time delay could be set was of the order of 0.02 microsecond for a low attenuation loss sample. This precision was caused by the limit of capability for reading the time delay on the adjustment knob. However, from epeated measurements of time delay in the same water-filled core tube, variations of about 0.1 microseconds were observed, depending on position along the core liner. These appear to be due to variations in the diameter or the wall thickness of the plastic core liner. A 0.1 microsecond difference corresponds approximately to a 5 meter/second difference in calculated sound speed.

The largest source of error is most likely due to the inability to control and measure temperature in the sediment sample at the time of sound speed measurements. Core samples were stored in a water-filled garbage can in an unheated area (usual temperature of water about 9° to 10° C) except during measurements. A few of the cores were slightly longer than the cans and this undoubtedly lead to temperature gradients in the core. An accurate assessment of the error due to temperature variability is not possible. Estimates of the maximum temperature effect can be had from efforts to repeat measurements after a time interval of a few hours or a day.

An example is Core D-2 wherein the time-spaced measured sound speeds differed on the order of 5 to 10 meters per second. Care was taken not to measure sound speed across core areas where small fissures or other signs of disturbance were visually evident.

Results of the sound speed observations, corrected to a temperature of 10°C are presented as part of Table 3.

IV. Sediment Mass-Physical-Property Determinations

Conventional soil testing procedures were used to determine wet density, porosity, and water content of the sediment samples[4]. A specimen of known volume was taken from selected regions of the cores or from the Shipek grab-samples, weighed wet, dried, and then weighed again.

Letting W_w = weight of specimen, wet

W_d = weight of specimen, dry

V = volume of specimen

The wet density, $\rho = W_w/V$.

The porosity, n, is the fraction of the total volume occupied by water, and is calculated from

$$n = \frac{W_w - W_d}{V}$$

Porosity is often expressed as a percentage.

The water content, w, another sediment parameter of interest which is often expressed as a percentage, is the ratio of the weight of water in the sample to the weight of the solids in the sample.

$$w = \frac{W_w - W_d}{W_d}$$

The containers used for measuring the volume of the specimens were made from thin-walled stainless steel tubing of nominal dimensions one inch long and one inch in diameter. In most cases, these cylinders were pressed into the sediment sample and the ends were squared off using a spatula. In some cases, remolding of the sediment was necessary to obtain a properly filled container. For the very fluid specimens a spoon was used to transfer sediment into a cup consisting of one of these cylinders with a plastic cap on one end.

Weight of the wet specimens was determined to the nearest one-tenth milligram within two hours after preparation with due care taken to humidify the samples. Drying was accomplished by leaving specimens in an oven maintained at 105° to 110°C for 20 hours or more. Care was also taken to only remove four or five samples at a time from the oven for weighing to preclude hygroscopic weight gain from room humidity. Values of wet density and porosity, resulting from the weighings and sediment characteristic calculations are presented in Table 3.

Most of the sample regions used for the above measurements were also selected for determination of sediment grain size distribution. Choice of specimens was based on a desire to get representative coverage of many different areas of the weapon's test ranges and to get information about gradients in a few locations. Mr. Dick Roberts of the University of Washington's Department of Oceanography Oceanography Technical Services, performed the grain size analyses. The percentage weights in the major textural groups, i.e., gravel, sand, silt and clay, and the grain size statistical data from the moment method are also listed in Table 3.

V. Sediment Data Collected by Other Investigators

Some data on sediment properties in areas of interest to this report were kindly made available to us by the University of British Columbia Department of Oceanography. Their surveys in the Strait of Geogria include several stations on or adjacent to the range at Nanoose and the range at Jervis Inlet. The locations of the Georgia Strait stations are shown on the charts in Figure 5, 6, and 7. Abstracts from their data reports[1], including the grain size analyses, are presented in Table 4.

In addition, we had available data collected by the Applied Physics Laboratory of the University of Washington[2]. Their stations are shown in Fig. 4. Their tabulated results are presented in Table 5. The values of water content were used to estimate a porosity value, assuming a typical value of grain specific gravity of 2.7.

The acoustic property estimates for these areas are included in the results section.

VI. Models for Absorption of Sound in Sediments

The sediment attenuation models developed by Hamilton[5,6,8] permit an estimate of the absorption coefficient for sound waves based on sediment porosity and mean grain size. These models were formulated from analysis of a large amount of data, much of it Hamilton's, and are applicable to a wide variety of sediment types.

The dependence of sound absorption on frequency in most sediments is given approximately by $\alpha = k\,f$ where α is the attenuation coefficent for plane waves due to absorption, in dB/m, f is the frequency in kHz and k is an empirical constant.

The linear dependence of α on frequency is approximate but very closely realized for most terrigenous sediments. The coefficient k is correlatable to grain size or to porosity. Hamilton[5] gives the following regression equations for k in terms of porosity, n, in percent or in terms of mean grain size M_z in phi units. ($\phi = -\log$ of grain diameter in mm.)

<u>Course, medium, and fine sand</u>: ($36 \le n \le 46.7\%$ or $0 \le \phi \le 2.6$)

$$k = 0.2747 + 0.00527\,n$$

or

$$k = 0.4556 + 0.0245\,M_z$$

<u>Very fine sand and lower porosity mixed sizes</u>: ($46.7 \le n \le 52\%$ or $2.6 \le \phi \le 4.5$)

$$k = 0.4903\,n - 1.7688$$

or

$$k = 0.1978 + 0.1245\,M_z$$

Mixed sizes: $(52 \leq n \leq 65\%$ or $4.5 \leq \phi \leq 6.0)$

$$k = 3.3232 - 0.0489\ n$$

or

$$k - 8.0399 - 2.5228\ M_z + 0.20098\ M_z^{\ 2}$$

Silt Clays: $(65 \leq n \leq 90\%$ or $6.0 \leq \phi \leq 9.5)$

$$k = 0.7602 - 0.01487\ n + 0.000078\ n^2$$

or

$$k = 0.9431 - 0.2041\ M_z + 0.0117\ M_z^{\ 2}$$

The graphs relating k to mean grain size, M_z , or percentage porosity, n, from Hamilton's papers[5,6] are reproduced in Figures 8, 9 and 10. The solid lines represent the regression equations given above. The graphs also show some of the variability in the measured values of absorption constant k. Most of the data fall within the dotted lines in these graphs. Based on the Hamilton models for determining the attenuation coefficient k, the expected values of k in dB/m/kHz for each of the stations and for various depths below the mudline are tabulated and discussed in the results section.

VII. Discussion of Results

A. Laboratory measurements and observations

All of the samples from the deeper parts of Dabob Bay and some of those from shallow water areas near Keyport are very soft, high porosity (usually 70 to 80 percent) clays or silty-clays. This is consistent with other studies of the sediments from Dabob Bay.[7] The thickness of the soft mud layer was not ascertained during our sampling, but it is believed that they are rather thick. It was noted during sample collection that the coring tool would penetrate sometimes as much as 12 feet into the sediment, although the maximum core length was about four feet.

In many of the samples, the top-most one or two centimeters was very fluid-like with a density only slightly greater than that of water. There were usually fairly strong negative sound speed gradients and positive density gradients in the top several centimeters and very weak gradients below that depth. The sound speed in saturated silt-clay sediment is typically one to two percent less than the speed of sound in the water. This was confirmed in several cores in which sound speed could be measured in the sea water immediately above the sediment.

Descriptors which apply to a number of the samples collected from the shallower parts of Dabob Bay and in shallow-water areas around Keyport (see figure (3)) are sandy mud, sand and gravel and sand with mud and shells. The porosity in these is significantly less than in the silty clays, typically 35 to 55 percent, the density is higher and the sound speed is significantly higher than that in the sea water. In a few cases of the very coarse samples, accurate sound speed measurements were precluded because of the larger sound absorption.

During visual examination of the cores at the time of recovery, we were not able to observe the presence of gas bubbles in the sediment. Because of their importance in affecting acoustic properties of the sediment, the possibility of the existence of gas bubbles cannot be ignored. These sediments do contain significant amounts of organic materials and gas-filled cracks did develop in some cores after several days of storage. The odor of hydrogen sulfide was very strong during cutting of the cores, particularly after several days.

The measured properties of samples collected from the Nanoose Range area by the University of British Columbia (UBC) and the Applied Physics Laboratory of the University of Washington (APL) are rather similar to those collected by us in the deeper parts of Dabob Bay.

B. Estimates of sound absorption

The models developed by Hamilton[5,6,8] and described briefly in Chapter VI permit making of an estimate of the sound absorption coefficient in saturated surficial sediments, based on either the porosity or the mean grain size. Using Hamilton's regression equations for k as a function of porosity, the values of k for all the silty clays lie between .05 and 0.1 dB/m/kHz. For most of the sandy or gravely sediment samples, a value of k of about 0.5 is predicted.

Since there is a significant amount of variability in the data used in generating the regression equations, there is a possibility that the absorption in these sediments may differ by as much as a factor of two from this prediction.

As an example, for a silty clay for which $k = 0.1$, the sound absorption coefficient, α, would have the value

$$\alpha = 0.1 \ f \ \text{dB/m}$$

where f is the frequency in kHz. Thus, at, say 20 kHz, the absorption coefficient would be about 2 dB/m.

C. The Concern for the Existence of Gas Bubbles

The possiblity that gas bubbles may exist in some parts of the sediments at certain times during the year should be considered for the reasons given in the following paragraphs.

Hampton and Anderson[9] conducted acoustic measurements in constructed sediments which indicated that the presence of gas dominates the observed behavior. They quoted the work of others who have observed absorption coefficients which are orders of magnitude larger than that in saturated sediments. They also point out that the effect of gas bubbles is to cause a significant decrease in the sound speed and that the acoustic reflectivity is greatly enhanced.

Schubel[10] observed that in Chesapeake Bay there exist regions of sediment which have high reflectivity and poor penetration of sound (from seismic profile records) compared to adjacent regions. That these differences are most likely due to gas bubbles was shown by the greater static compressibility of cores from these areas, compared to others and by x-ray measurements which showed voids in these cores which were not present in cores from the less turbid regions.

Observations[11] have been made of the phase inversion of a pressure wave upon reflection from the sediments in Dabob Bay which could be explained by bubbles in the sediment.

Dr. David Weston (private communication) described observations of worm holes in shallow estuarine sediments during experiments he conducted many years ago with Dr. A.B. Wood[12]. Estimates of the volume of gas contained in the sediment and calculation of the effects this would have on acoustic propagation over and into such a boundary were consistent with acoustic measurements. There is a strong possiblitiy that if gases are present, the concentration and bubble size vary seasonally.

D. Expected Gradients in Properties

Our measurements do show that there are rapid changes in the physical properties of the sediments in the top few centimeters. In the soft sediments, there appear to be weak positive gradients in sound speed and some decreases in porosity with depth in the top meter. However, the short length of our cores and the limited precision of the sound speed measurement prohibit use of our results to predict properties at greater depths.

The data presented in Reference 6 indicate that the approximate values of the gradients for porosity and sound speed in a saturated silt-clay sediment are -0.07 percent per meter and +1.3 per sec, respectively.

If the porosity changes so slowly as this, the increase in the absorption constant k with increasing depth is probably not large enough to create significant problems in the top 10 meters of sediment.

VIII. Conclusions and Recommendations

The measured values of density, porosity, sound speeds and grain size correspond well to values reported by others for similar sediments. We believe that if the silty-clay sediments are fully saturated, the values of the absorption coefficient calculated using Hamilton's model should be valid for materials having similar properties in the Nanoose Range and that these values of absorption, while much larger than for sea water, are not large enough to preclude the effective use of an acoustic imaging system in these soft sediments at a moderate frequency.

If bubbles are present in the sediment, the absorption coefficient would be much larger and reverberation levels should increase significantly. Both effects would significantly reduce the effectiveness of an acoustic imaging system. Further, there is the possibility that the bubble effects may be seasonal.

We were not successful in locating a shallow water area conveniently close to land in the Keyport area for use in preliminary acoustic imaging experiments. There are some areas near Keyport but they are probably far enough from land to preclude using land-based instrumentation for the test.

It is recommended that development work on acoustic imaging systems be continued with an operating frequency which is as low as can be accomodated. A noteworthy caveat is that turbid or "gassy" bottom sediments are highly attenuating and reflecting at any frequency and can, therefore, potentially limit sound penetration into the bottom to only a very few meters. This could preclude acoustic detection of torpedoes buried 20 feet or more if they bury in sediment structures entailing near-surface gas saturated layers.

It should be noted that, at the present time, it is not known if or to what extent such gassy sediments exist in areas of interest. Therefore, it is recommended that, whenever opportunities arise to conduct experiments as part of other operations, they be exploited. Use of side-scan sonars, sub-bottom profilers and acoustic reverberation or target strength measuring systems could provide useful information on variability of acoustic properties in areas of interest.

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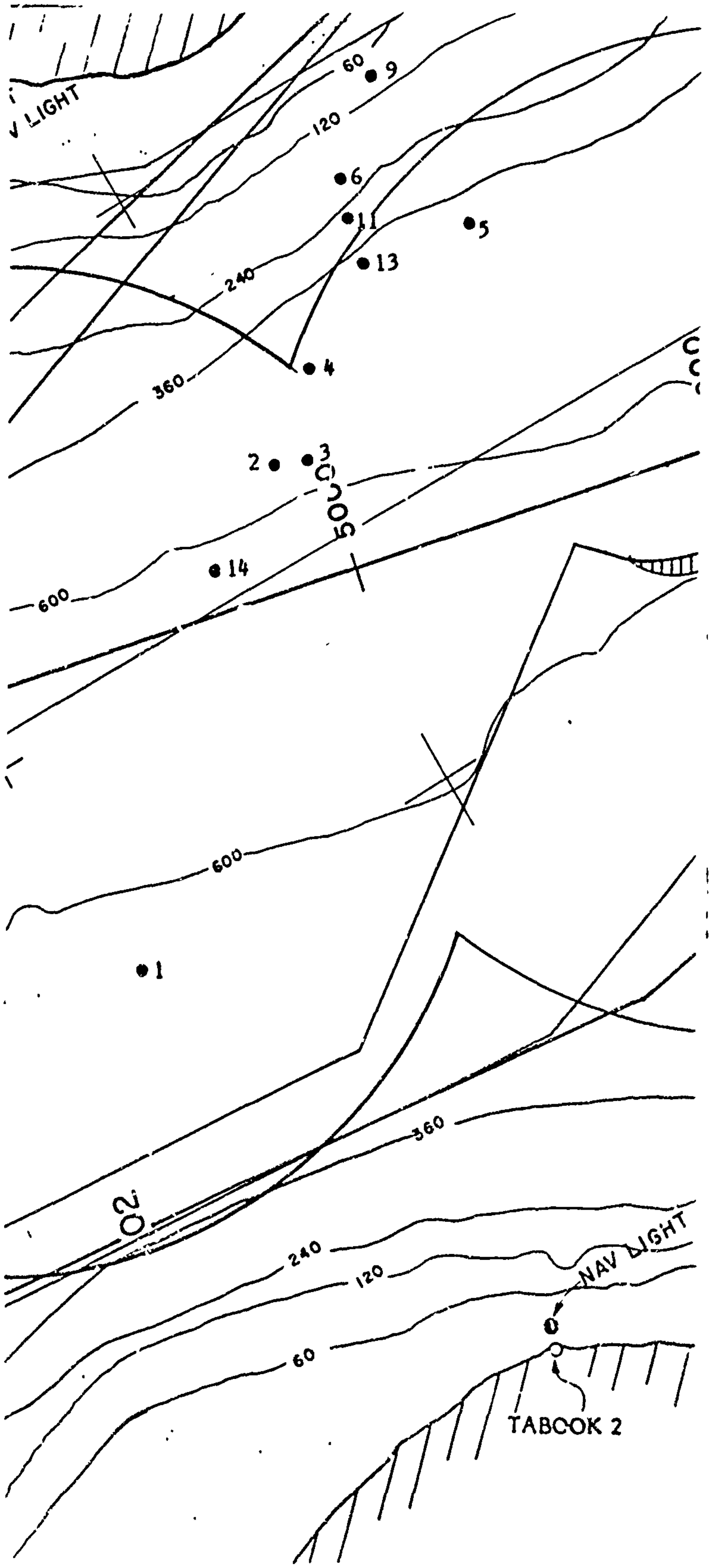

Fig. 1. Chart showing locations of Stations 1-14 in Dabob Bay.

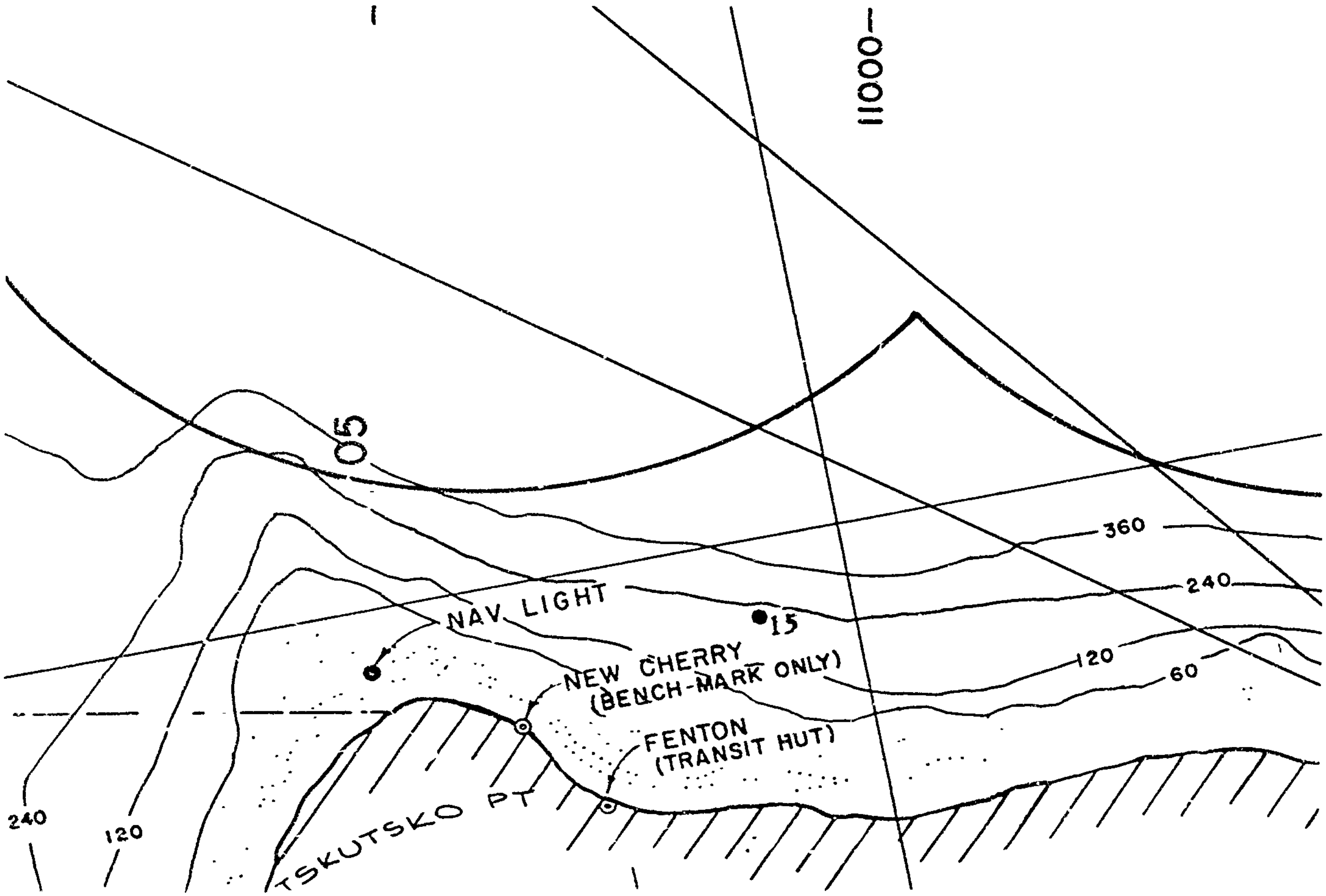

Fig. 2. Chart showing location of Station 15 in Dabob Bay.

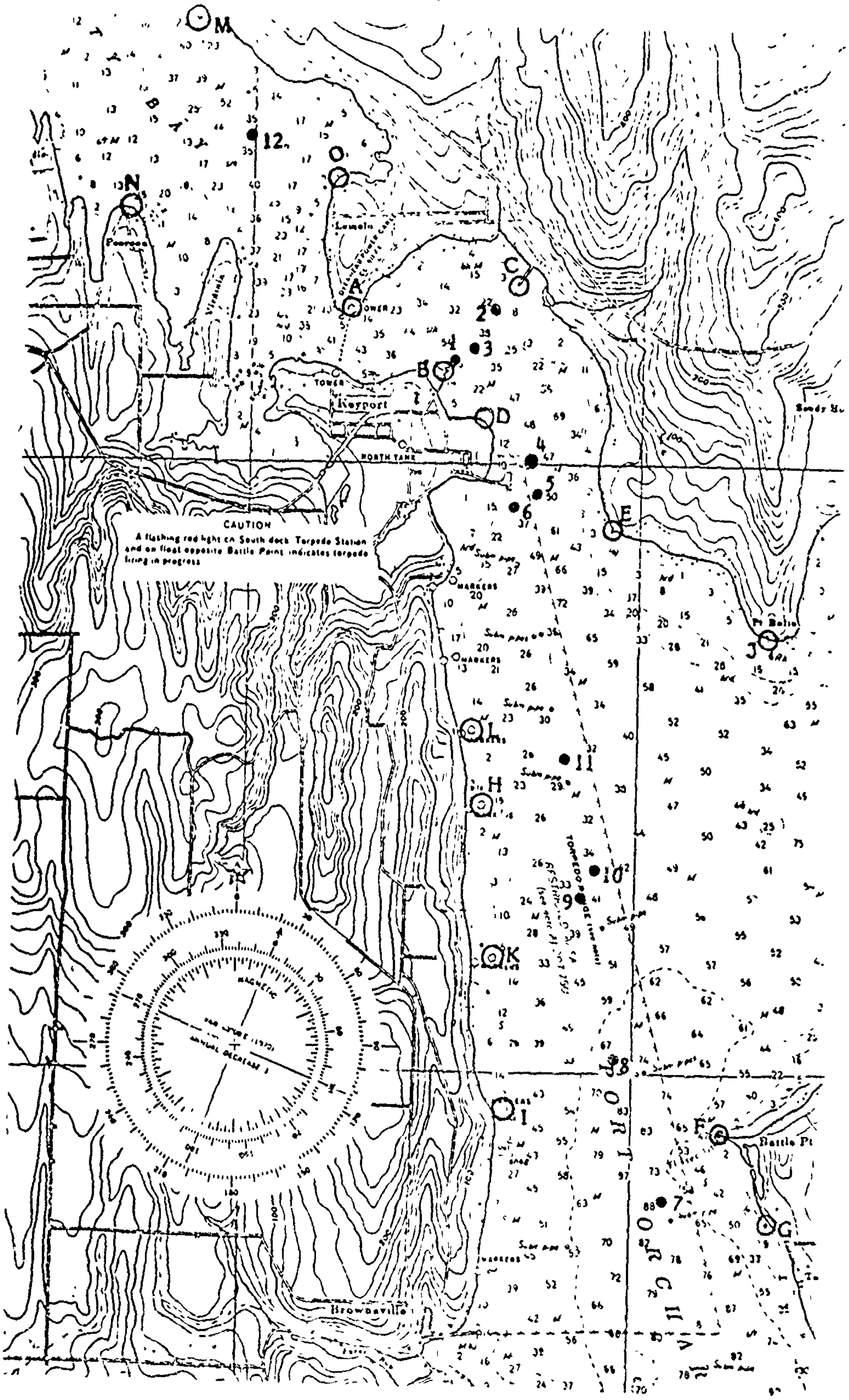

Fig. 3. Chart showing locations of shallow water Stations near Keyport.

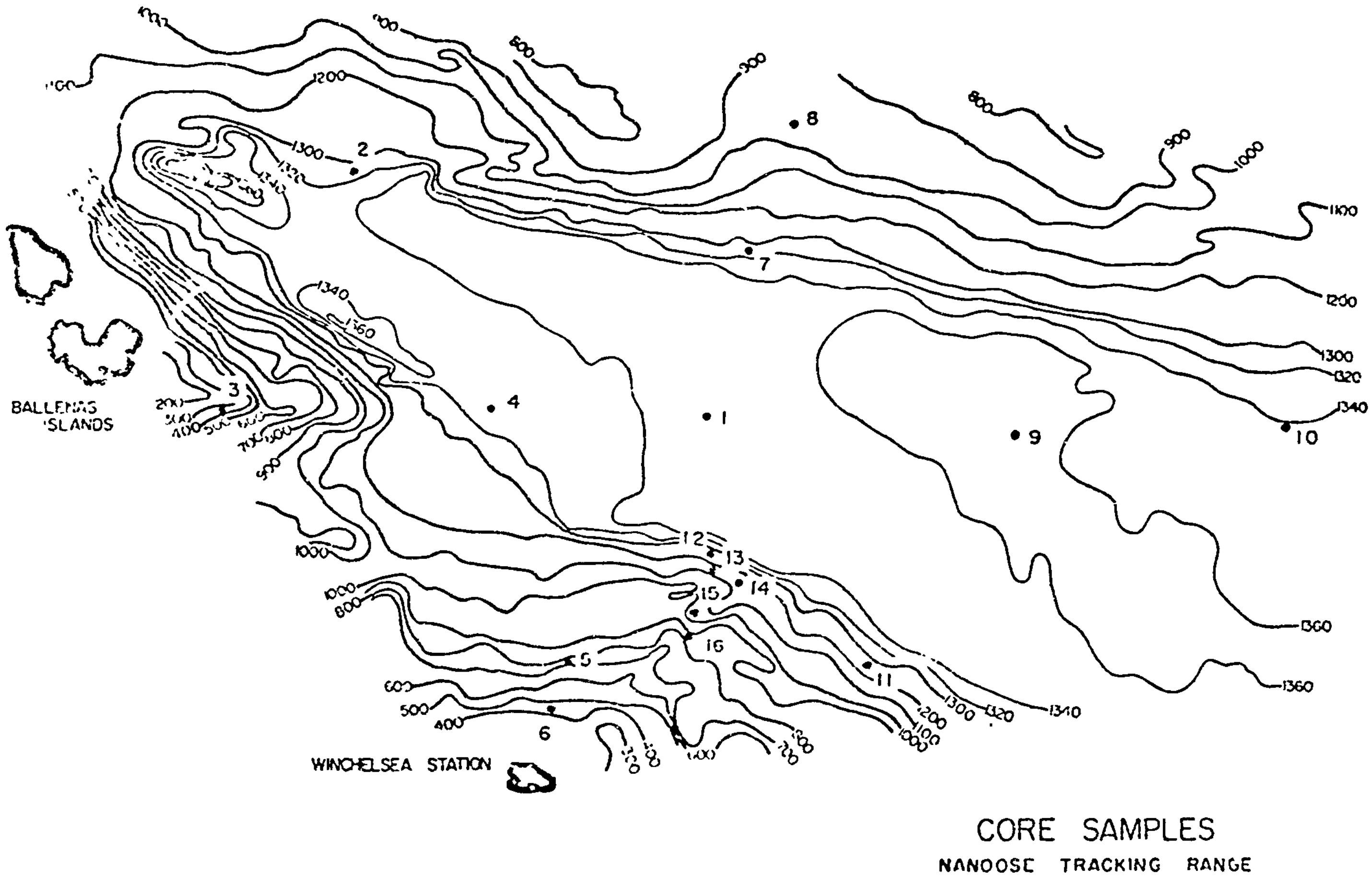

Fig. 4. Chart showing locations in Strait of Georgia of Stations used by the Applied Physics Laboratory, University of Washington (Ref. 2).

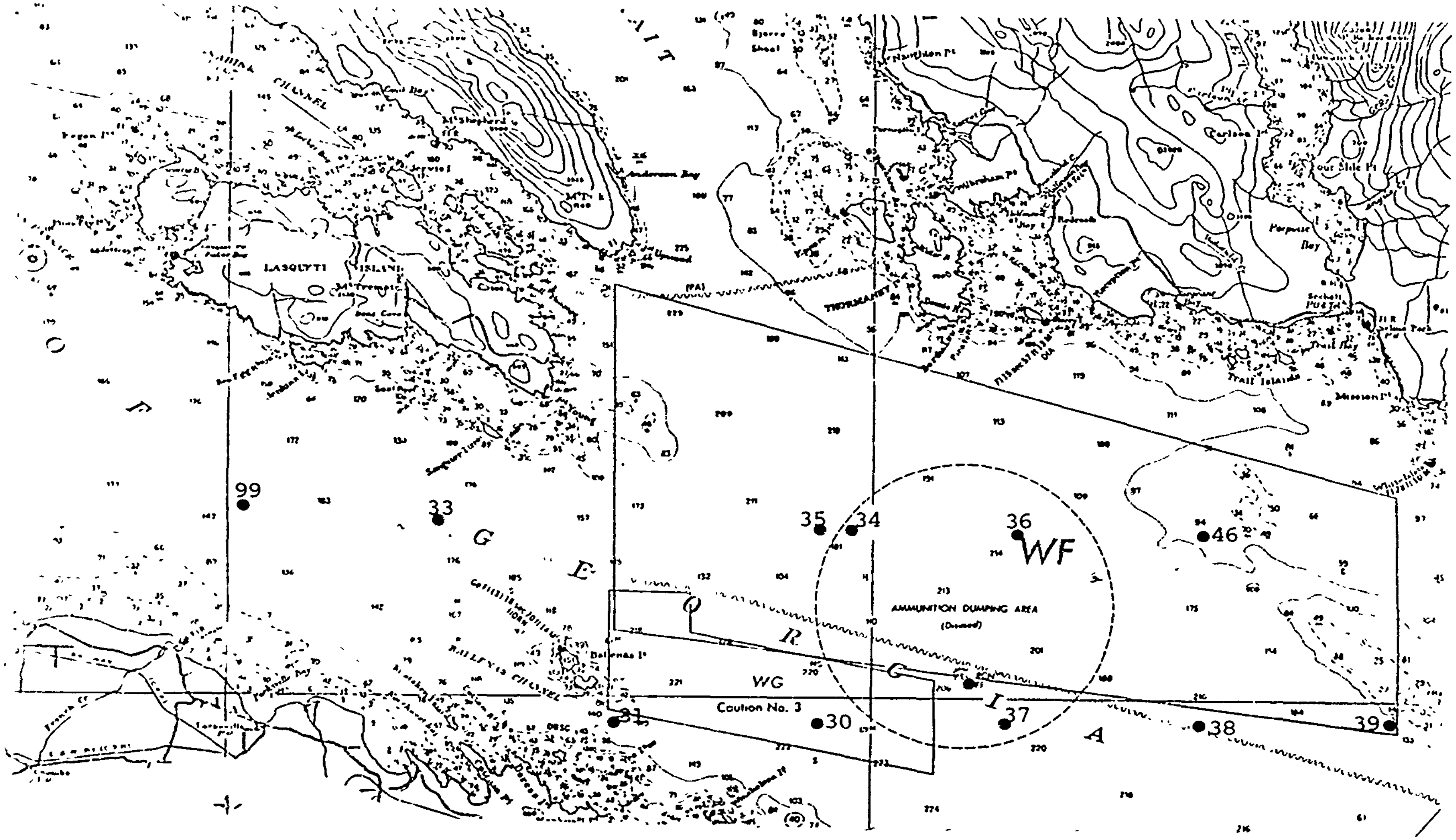

Fig. 5. Chart of locations in Strait of Georgia of Stations for samples taken by University of British Columbia (Ref. 1). Enlarged sections are shown on Figures 6 and 7.

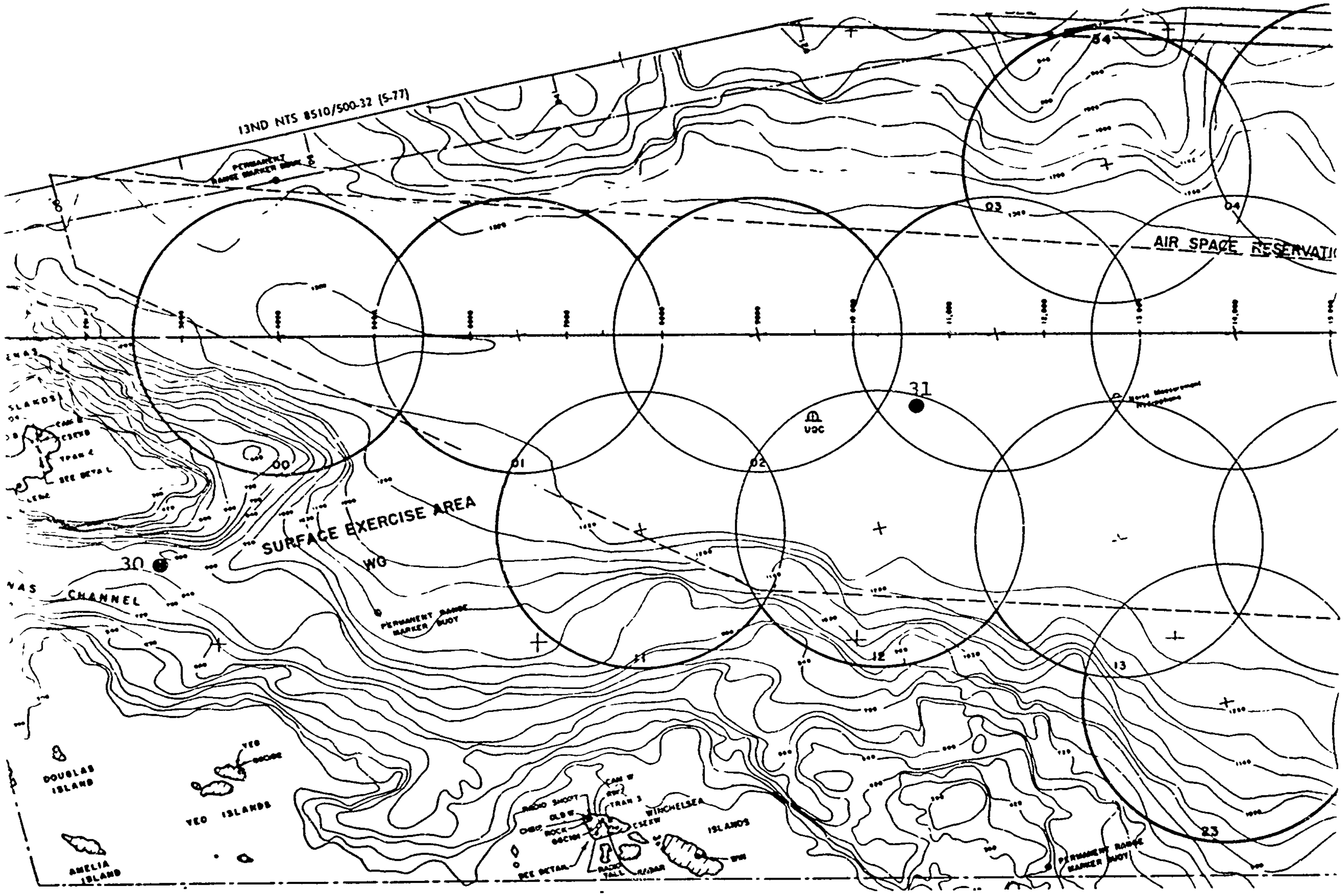

Fig. 6. Enlarged Western section of chart of locations of UBC Stations on Nanoose Range. (Ref. 1)

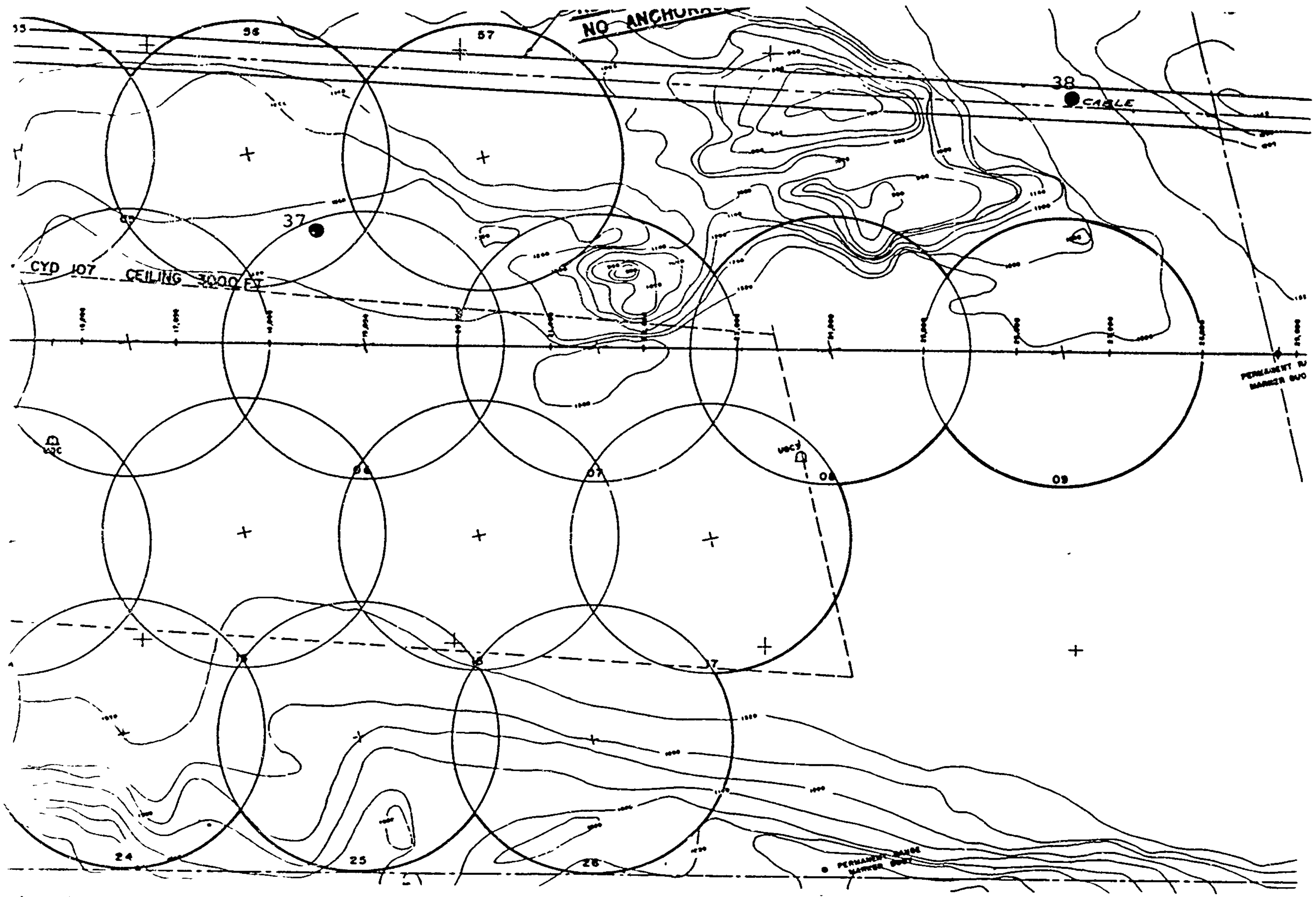

Fig. 7. Enlarged Eastern section of chart of locations of UBC Stations on Nanoose Range (Ref. 1).

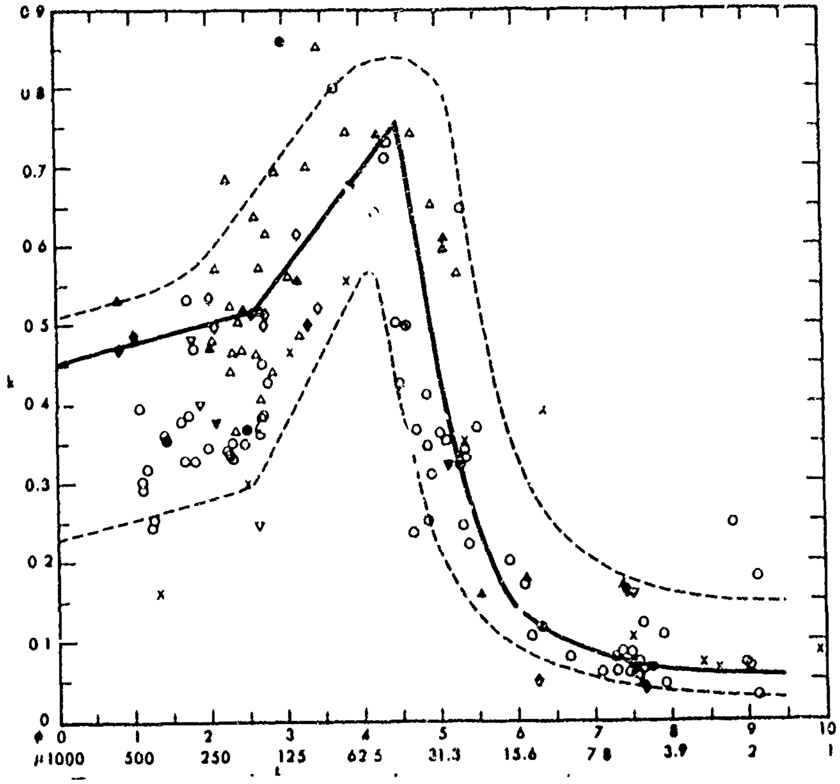

Fig. 8. Sound absorption constant, k, for fine sediments as a function of mean grain size in ϕ units and in micrometers (from Hamilton (Ref. 5)).

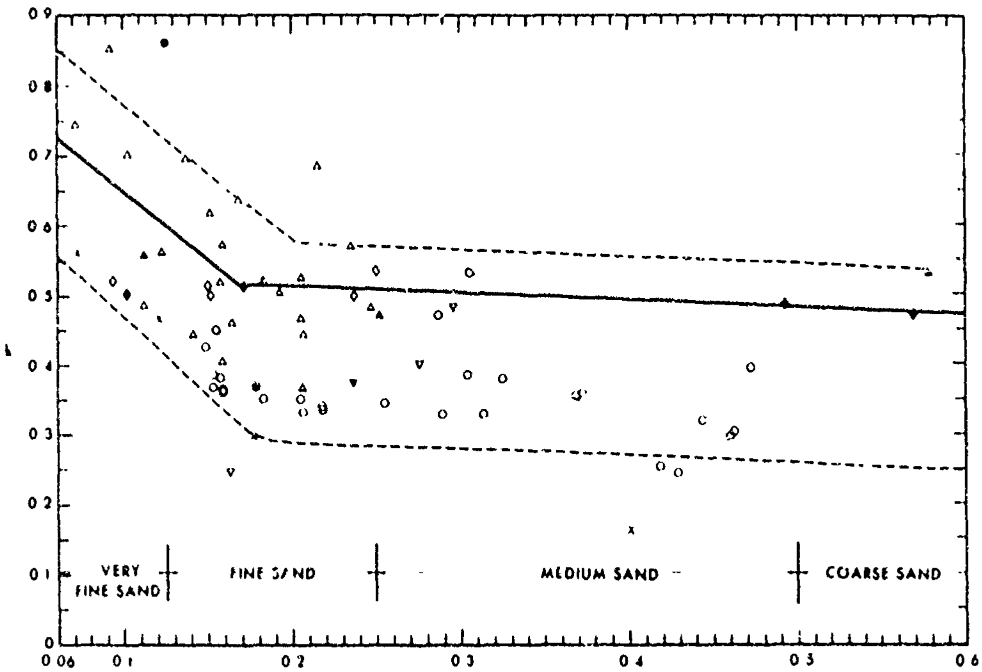

Fig. 9. Sound absorption constant, k, for sandy sediments as a function of mean grain size in millimeters (from Hamilton (Ref. 5)).

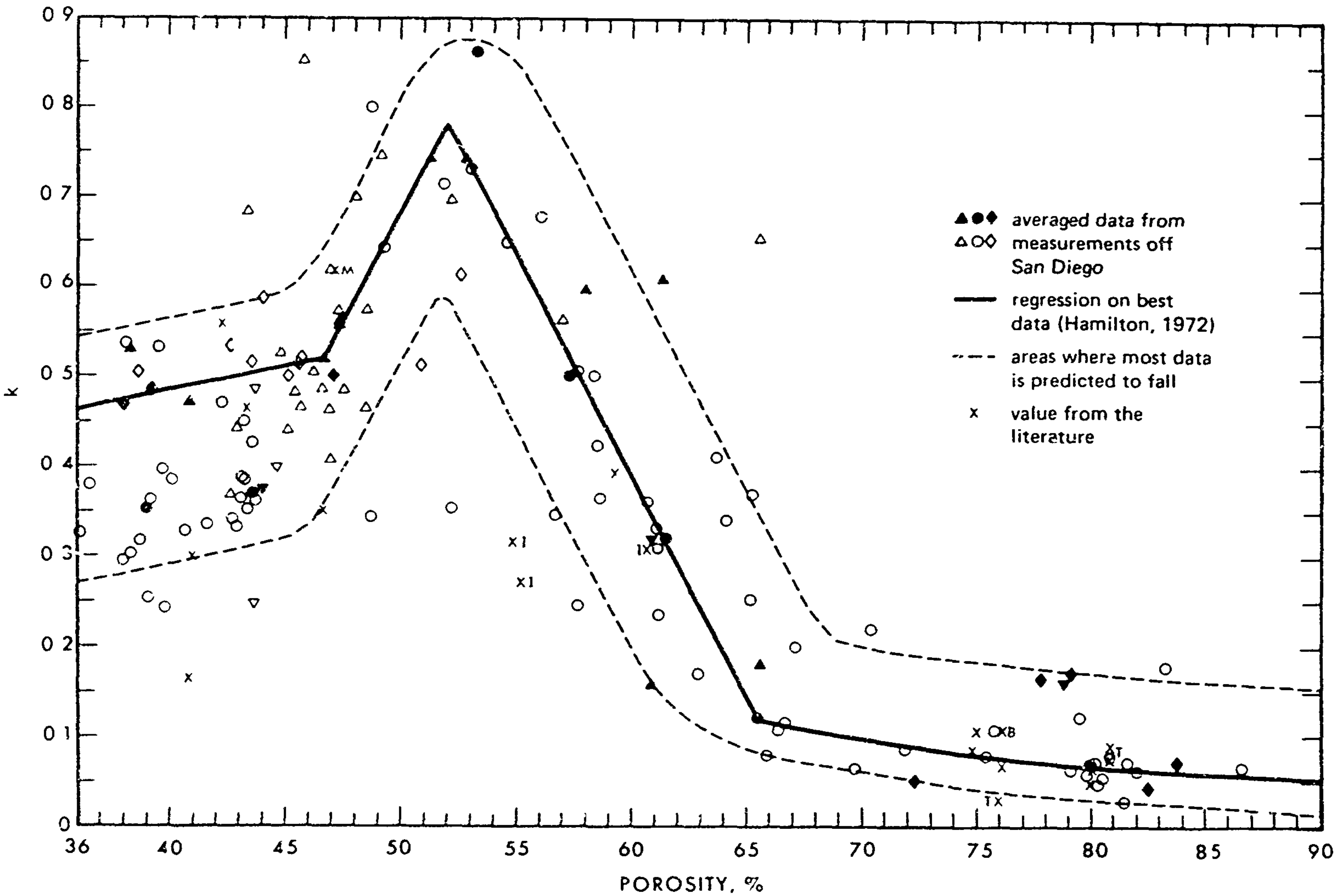

Fig. 10. Sound absorption constant, k, as a function of sediment porosity for various natural, saturated, surficial sediments (from Hamilton (Ref. 6)).

TABLE 1. LOCATIONS OF STATIONS AND TYPES OF SAMPLES TAKEN IN DABOB BAY (See Charts, Fig. 1 and 2)

Date: 5 February 1979

Station	Water Depth (feet)	Type of Sample: Gravity Corer	Type of Sample: Shipek Grab	Range Position (yards): Range Center Line	Range Position (yards): Cross. Range	Length of Core (inches)	Comment
1	590	X		5,822	760E	40	Olive green mud, Very fluid at top, Bottom of Core disturbed
2	600	X		5,100	290W	40	Penetration 12 ft., Soft mud, very fluid top layer
3	510	X		5,040	285W	35	Penetration 6 ft., light gray-green to brown-green mud
4	495	X		4,958	487W	35	Mottled light-green to dark brown mud. Some black streaks
5	390	X		4,480	700W	30	Penetration 5 ft. Top layer very loose. Lower parts sandy
6	240	X		4,750	900W	6	Gravel and sand
9	150		X	4,585	1,111W		
11	318		X	4,760	800W		
13	426		X	4,777	680W		
14	—		X	5,342	100W		
15	216	X		11,210	1,320E	5	Small penetration. Sample in core nose only. Sandy mud

TABLE 2. LOCATING DISTANCES FOR SHALLOW WATER GRAVITY CORES TAKEN NEAR KEYPORT (See Fig. 3)

Date: 7 February 1979

Radar Ranges to Landmarks (LM) in Yards

Core	Water Depth (feet)	LM	Range	LM	Range	LM	Range	Length of Core Inches	Comment
1	46	A	750	B	120	C	650		Little penetration, No sample retrieved
2	24	A	1,000	B	500	C	250	10	Small penetration, Sandy silt
3	61	A	800	B	200	C	530	4	Sandy Mud, little penetration
4	50	C	1,200	D	450	E	750	21	Soft mud, Gray-green color with some sand
5	52	C	1,400	D	600	E	600	8	Gravel, sand and shells in mud
6	41	C	1,500	D	600	E	800	10	Sandy mud with shells and a worm
7	81	F	600	G	750	I	1,250	16	Sandy with some shells
8	73	F	950	I	850	J	3,050	30	Gray-green mud with some sand
9	44	F	1,900	K	750	J	2,200	35	Mottled gray-green mud. Mud on weights
10	43	K	950	H	900	F	2,000	41	Silty mud at top, mottled dark-gray with some sand in middle
11	36	K	1,450	L	650	J	1,650	34	Silty mud at top, sandy with mottled colors deeper in core
12	52	M	850	N	700	O	700		Little penetration, Gravel, sand and shells in core catcher only

TABLE VALUES OF PROPERTIES MEASURED IN THE LABORATORY FOR SAMPLES COLLECTED IN DABOB BAY AND SHALLOW WATER AREAS NEAR KEYPORT

PROPERTIES MEASURED IN THE LABORATORY						MAJOR TEXTURAL GROUPS				GRAIN SIZE ANALYSIS			
Station	Sample Number	Depth in core cm	Sound Speed m/sec (10°C)	Wet Density kg/m^3	Porosity percent	Gravel	Sand (Percentages)	Silt (Percentages)	Clay	Mean Grain Size	Stand. Dev.	Skew.	Kurt.
											ϕ Units		
D-1	3	1		1055	87.6	—	0.84	42.50	56.67	8.72	2.31	-0.33	2.36
		4	1452										
		13	1448										
		23	1448										
		31	1446										
		40	1447										
		49	1446										
	2	56		1254	86.5								
		61	1450										
		68	1446										
		76	1446										
		86	1447										
		89	1444										
	1	91		1315	80.0	—	14.08	37.77	48.14	7.74	2.87	-0.33	2.00
		98	1448										
		100	1455										
	44	>100		1254	80.9								
D-2	5	1	1483	1076	85.1	0.04	0.25	36.53	63.18	8.83	2.11	-0.34	2.24
		4	1475										
		8	1476										
		11	1475										
		14	1468										
		16	1472										
		37	1463										
		43	1465										
		47	1462										
	6	51	1465	1243	85.1	0.08	0.87	44.17	54.88	8.39	2.09	-0.22	2.88

(Continued)

TABLE 3 (Con't)

Station	Sample Number	Depth in core cm	Sound Speed m/sec (10°C)	Wet Density kg/m^3	Porosity percent	Gravel	Sand	Silt	Clay	Mean Grain Size	Stand. Dev.	Skew.	Kurt.
							Percentages					ϕ Units	
D-2 (Cont.)		84	1462										
		92	1463										
	41	12		1297	86.8	—	0.49	39.13	60.38	[illegible]	2.14	-0.22	2.00
D-3	Sea Water		1476										
	8	1	1463	1076	87.3								
		4	1560										
		8	1460										
		16	1455										
		26	1455										
		34	1454										
		44	1448										
	9	48	1454	1269	85.0								
		54	1449										
		63	1445										
		71	1450										
	7	76		1288	81.5								
		80	1448										
D-4	11	1		1056	86.3	—	0.74	36.29	62.97	8.89	2.19	-0.43	2.38
		5	1474										
		14	1478										
		24	1469										
		31	1466										
		40	1463										
		49	1461										
	12	53		1267	84.3	—	0.86	41.70	57.44	8.61	2.26	-0.27	2.19
		66	1454										
	10	74		1255	87.3	—	0.33	40.53	59.14	8.74	2.17	-0.18	1.90
		76	1454										
		83	1461										
D-5	Sea Water		1486										
	14	1		1263	79.8								
		3	1476										
		12	1497										
		21	1556										

(Continued)

TABLE 3 (Cont'd)

Station	Sample Number	Depth in core cm	Sound Speed m/sec (10°C)	Wet Density kg/m^3	Porosity percent	Gravel	Sand	Silt	Clay	Mean Grain Size	Stand. Dev.	Skew. ϕ Units	Kurt.
						Percentages							
D-5 (Cont.)		31	1517										
		39	1537										
	15	43		1746	56.2	27.29	16.89	38.71	17.12	3.48	4.76	-0.17	1.89
		50	1603										
		55	1483										
		65	1483										
		73	1483										
	13	76		1780	50.8								
D-6	16	7		2063	45.4	40.86	25.29	24.17	9.69	1.46	4.45	0.43	2.15
D-8	42			2158	36.8								
D-9	43			2023	44.6								
D-11	45			1202	89.2								
D-15	37	3		2119	45.5	29.8	59.19	5.46	5.56	0.96	3.61	0.52	3.52
K-2	Sea Water		1491										
	31	1		1627	66.2	0.01	83.31	8.81	7.87	2.99	2.46	2.11	6.73
		3	1653										
		6	1596										
		16	1630										
		20	1694										
K-3	38			1537	66.0	0.28	54.45	23.49	21.78	4.50	3.58	0.57	1.92

(Continued)

TABLE 3 (Cont'd)

Station	Sample Number	Depth in core cm	Sound Speed m/sec (10°C)	Wet Density kg/m³	Porosity percent	Gravel	Sand	Silt	Clay	Mean Grain Size	Stand. Dev.	Skew. ϕ Units	Kurt.
							Percentages						
K-4	21	1		1289	72.7	0.31	49.47	30.35	19.87	5.00	3.09	0.66	2.35
		6	1510										
		15	1528										
	22	18		1794	57.4	0.67	76.78	14.62	7.93	3.24	2.55	1.49	4.94
		24	1526										
		33	1573										
		42	1627										
		51	1644										
	20	53		2003	38.6	7.38	80.57	7.67	4.38	2.17	2.60	0.72	6.25
K-5	33	1		1955	37.6	57.75	35.92	3.23	3.10	-0.57	2.79	2.12	8.22
		8	1954										
		14	1504										
	34	18		1451	70.8	—	42.98	36.98	20.04	5.34	2.83	0.59	2.51
K-6	35	1		1279	77.3	3.65	44.11	27.54	24.71	5.11	3.77	0.27	2.16
	36	9		1439	67.2	0.72	29.88	42.20	27.19	6.02	2.99	0.17	2.27
K-7	28	1		1222	81.5	4.33	30.29	39.57	25.81	5.57	3.50	-0.22	2.87
		12	1532										
		20	1584										
		29	1931										
	29	41		1797	47.1	0.28	81.43	11.64	6.65	3.05	2.34	1.84	6.25
	32	41		1949	39.5	3.92	82.07	9.39	4.62	2.38	2.35	1.43	7.85
K-8	18	1		1133	80.3	—	3.32	57.01	39.67	7.41	2.37	0.16	2.21
		5	1468										
		14	1463										
		23	1472										
	19	33	1467	1359	81.5	0.16	3.96	76.60	19.28	6.86	2.31	0.72	3.39
		43	1463										
		60	1454										
	17	64		1335	81.4	—	3.04	72.57	24.39	7.11	2.09	0.49	3.20

(Continued)

TABLE 3 (Cont'd)

Station	Sample Number	Depth in core cm	Sound Speed m/sec (10°C)	Wet Density kg/m^3	Porosity percent	Gravel	Sand (Percentages)	Silt (Percentages)	Clay	Mean Grain Size	Stand. Dev.	Skew. ϕ Units	Kurt.
K-9	27	1		1318	78.0	—	3.65	75.40	20.94	6.63	2.22	0.68	3.04
		6	1467										
		37	1447										
	26	43		1396	82.4	—	5.17	63.06	31.77	7.04	2.35	0.12	2.76
		55	1438										
		65	1447										
K-10	24	1		1187	80.7	—	3.54	63.19	33.27	7.30	2.37	0.35	2.34
		14	1564										
		31	1449										
		44	1440										
	25	51		1325	77.9	—	4.30	83.65	12.06	6.52	1.87	0.80	4.49
		64	1422										
	23	79		1391	76.1	—	9.68	82.[illegible]	9.08	6.25	1.99	0.61	4.84
		81.3	1427										
K-11	47	1		1327	87.4	1.33	7.11	65.[illegible]	25.87	6.70	2.49	-0.25	4.44
		6	1470										
		24	1449										
		34	1467										
	46	39		1336	76.7	—	9.62	80.87	9.52	6.22	1.89	0.72	4.90
		44	1463										
		53	1457										
	48	64		1358	76.2	0.39	5.06	73.49	21.06	6.85	2.11	0.21	4.08

TABLE 4. PROPERTIES OF SAMPLES FROM STRAIT OF GEORGIA AND JERVIS INLET TAKEN BY UNIVERSITY OF BRITISH COLUMBIA. INSTITUTE OF OCEANOGRAPHY, (FROM REFERENCE 1)

Locations of Strait of Georgia Stations are shown in Figures 5, 6, and 7.

* C = gravity corer S = Shipek Sampler

Area	Station No.	LAT °North'		LON °West'		Depth m	Gear*	Sand Percentages	Silt	Clay	Mean Grain Size	Stand. Dev. ϕ Units	Skew.
Georgia	13	49	7.8	123	19.2	112	C	6	64	30	6.4	1.70	0.24
Straits	28	49	15.5	123	55.7	370	C	1	28	71	9.0	1.30	0.08
Cruises 60/2,60/S	30	49	19.4	124	1.8	430	C	1	29	70	8.9	1.20	0.08
	31	49	19.5	124	7.9	250	C	67	11	22	1.8	4.90	-0.06
Data Report 20	33	49	23.5	124	13.8	340	C	0	24	76	9.2	1.15	0.04
	34	49	23.5	124	0.8	270	C	8	21	71	9.3	1.55	-0.03
	35	49	23.5	124	1.8	360	C	0.5	19.5	80	9.2	1.15	0.13
	36	49	23.4	123	55.5	420	C	2	27	71	9.2	1.30	-0.08
	37	49	19.5	123	55.8	395	C	0.5	28.5	71	8.9	1.55	0.29
	38	49	19.5	123	49.7	380	C	0	34	66	8.8	1.25	-0.04
	39	49	19.6	123	43.7	100	C	76	13	11	2.8	0.80	0.38
	46	49	23.5	123	49.7	170	C	0	22.5	77.5	9.35	1.35	0.07
	99	49	24.3	124	19.4	360	C	1	33	66	8.8	1.35	0.11
Jervis	Je1	49	43.3	124	15.4	230	S	9	34	57	8.5	2.00	-0.10
Inlet	Je2	49	46.3	124	09.0	585	S	3	42	55	8.3	1.90	-0.05
Cruise 60/8	Je3	49	47.7	124	02.2	670	S	1.5	36.5	62	8.9	1.85	0.00
	Je4	49	49.6	123	54.2	677	S	4	48	48	7.9	1.40	0.14
Data Report 22	Je5	49	51.7	123	56.6	660	S	5	44.5	50.5	8.1	2.30	-0.04
	Je6	49	59.4	123	59.0	560	S	64	26	10	3.4	1.10	0.02
	Je7	50	02.5	123	51.5	560	S	3	55	42	7.5	1.70	0.00
	Je8	50	05.3	123	46.7	470	S	69	20	11	3.0	1.20	0.33
	Je9	50	09.0	123	51.2	320	S	49	38	13	4.1	2.60	0.04

TABLE 5. DATA ON SAMPLES FROM NANOOSE TRACKING RANGE TAKEN BY APL, UNIVERSITY OF WASHINGTON (Reference 2). Positions of Stations are shown on Fig. 4.

CORE NUMBER	DEPTH (FEET)	SAMPLE DEPTH IN CORE (cm)	MAJOR TEXTURAL GROUPS (percentages) GRAVEL	SAND	SILT	CLAY	WATER** CONTENT (%)	ESTIMATED*** POROSITY PERCENT
APL-1-1	1330	0-2	—	0.65	48.26	51.09	168.22	82
APL-1-1		101-103b*	—	1.47	35.17	63.36	161.03	81
APL-1-2	1320	0-2	—	3.69	39.41	56.90	280.56	88
APL-1-2		110-112b	—	1.82	74.37	23.81	213.25	85
APL-1-3	430	0-2	—	29.43	27.82	42.75	212.51	85
APL-1-3		19.5-21.5b	—	6.70	29.59	63.71	208.33	85
APL-1-4	1323	0-2	—	2.91	43.65	53.44	273.82	88
APL-1-4		103-105b	—	0.69	38.61	60.70	212.35	85
APL-1-5	680	0-2	—	12.00	36.19	57.81	175.81	83
APL-1-5		27-29	24.25	1.88	33.16	40.71	13.32	26
APL-1-5		48-50b	39.65	14.90	28.12	17.32	15.87	30
APL-1-6	460	0-2	10.47	14.42	37.65	37.47	148.27	80
APL-1-6		38-40b	14.89	52.12	21.36	11.63	15.84	30
APL-1-7	1312	0-2	—	0.88	42.03	57.09	187.61	84
APL-1-7		108-110b	—	0.46	32.44	67.10	148.93	80
APL-1-8	930	0-2	—	2.63	33.33	64.04	166.49	82
APL-1-8		90.5-92.5b	—	0.25	28.55	71.20	138.52	79
APL-1-9	1352	0-2	—	0.24	36.13	63.63	197.41	84
APL-1-9		101-103b	—	2.85	40.40	56.66	290.03	89
APL-1-10	1330	0-2	—	0.78	41.88	57.34	194.91	84
APL-1-10		100-102b*	—	0.48	33.60	65.92	165.05	82
APL-1-11	1092	full short core	—	15.08	27.94	57.98	176.55	83
APL-1-11		clam shell	—	0.45	46.30	53.26	246.03	87

(Continued)

TABLE 5 (CONT.)

CORE NUMBER	DEPTH (FEET)	SAMPLE DEPTH IN CORE (cm)	GRAVEL	(percentages) SAND	SILT	CLAY	WATER** CONTENT (%)	POROSITY PERCENT
APL-1-12		0-2	—	1.59	38.34	60.07	268.16	88
APL-1-12		94-96b	—	0.51	37.82	61.67	216.12	85
APL-1-13		Clam Shell 0-2	—	2.13	34.65	63.22	220.65	86
APL-1-13		119-121b	—	0.84	30.77	68.39	142.21	79
APL-1-13				0.65	39.10	60.25	232.55	86
APL-1-14		0-2	—	3.44	37.33	59.23	231.39	86
APL-1-14		66-68b	—	9.92	34.87	55.21	182.55	83
APL-1-15		0-2	—	15.50	28.58	55.92	154.67	81
APL-1-15		27-29	—	0.84	40.31	58.85	125.00	77
APL-1-15		108-110b	—	1.21	44.31	54.48	105.37	74
APL-1-16		0-2	—	34.51	27.60	37.89	149.70	80
APL-1-16		50-52	—	1.29	48.41	50.29	100.[illegible]	75
APL-1-16		76.5-78.5b	—	[illegible].52	52.64	46.84	116.37	76

* b indicates bottom of core

** water content = $\frac{\text{weight of water}}{\text{weight of solids}}$

*** porosity = $\frac{\text{volume of water}}{\text{volume of sample}}$. These values assume a grain specific gravity of 2.7.

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